

Quasicrystals in Al Alloys

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Discovering quasicrystals (solids, as a rule intermetallics, that have 5-, 8-, 10- or 12-fold rotational symmetry and no translational symmetry in atomic packing) is considered to be one of the most prominent discoveries in material science of the second half of XX century. Quasicrystalline phases are now revealed in about 200 systems, most of them on Al base. Due to their specific atomic packing quasicrystals have a peculiar combination of physical and mechanical properties. There are distinguished two types of Al alloys with quasicrystalline phases: (i) quasicrystals in themselves; (ii) alloys with reinforcing quasicrystalline particles in α -Al matrix. A short review of the results in studying structure and mechanical properties of both alloy types with a peculiar attention to the results obtained in the IPMS is presented.

Quasicrystals are macroscopically brittle at temperatures lower than about $0.8T_m$ (e.g., 650 °C for Al-Cu-Fe quasicrystal), therefore alloys of the type 1 are used in the industry in the form of coatings. To Al-Cu-Fe and Al-Pd-Mn quasicrystals the system of indentation techniques developed in the IPMS (temperature and load dependence of hardness, construction of stress-strain curves at ambient temperature, determination of the plasticity characteristic δ_H , nanoindentation) was applied. The results are consistent with the concept of a phase transformation under the indenter into a more plastic phase. Stress-strain curves for quasicrystals are obtained first, they reveal stress softening, as in compression test at high temperatures in works of other authors published earlier.

Alloys of the type 2 alloyed with refractory transition metals are promising as elevated temperature Al alloys. The only way of manufacturing such alloys is rapid solidification. Powders of alloys Al-Fe-Cr-(Ti, Zr) that belong to the type 2 were first atomized with high-pressure water by original technology developed in the IPMS. Bulk samples for the investigation in the form of extruded rods were manufactured from these powders. Model melt-spun ribbons were studied too. The data of studying structure and tensile properties for alloys of 13 compositions in the interval of Al contents from 93 to 95.8 at. % are presented. Structure, phase composition and distribution of alloying elements between phases were studied by X-ray, SEM and TEM techniques. Some regularities of deformation and fracture mechanisms of rods under investigation as well as of quasicrystal stability depending on alloy chemical composition and manufacturing conditions were established. The best combination of tensile properties at 300 °C was obtained for alloy $Al_{94}Fe_{2.5}Cr_{2.5}Ti_1$ (YS = 286 MPa, UTS = 312 MPa, EL = 5.4 %) with the plasticity at ambient temperature EL = 8 %.

Influence of Sc on the Amorphization of Al Alloys

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Among Al alloys a very high tendency to amorphization is observed in alloys on Al-REM base. Sc is known for a many-sided improving action on Al alloys, and both Sc and REM belong to the IIIB group of the Periodic System. The data of Sc effect on the amorphization in Al alloys in the literature are absent. We investigated the alloys $\text{Al}_{100-x}\text{Sc}_x$, $\text{Al}_{91}\text{Ce}_{9-x}\text{Sc}_x$ and $\text{Al}_{85}\text{Ni}_{10}\text{Ce}_{5-x}\text{Sc}_x$ in the form of melt-spun ribbons. The investigation was carried out by X-ray, TEM, DSC and durometric techniques.

In Al-Sc alloys with Sc content to 13 at. % in our manufacturing conditions no amorphous phase was formed, at $x \approx 13$ at. % we first observed the formation of small quasicrystalline particles in α -Al matrix. The quasicrystalline phase appeared to be unstable and transformed to Al_3Sc intermetallic in 3 months holding at ambient temperature. Substituting Sc for Ce in two other systems lowered the tendency to amorphization. It was manifested in appearing small (of 5-10 nm) α -Al particles in amorphous matrix (at $x = 3$ in Al-Ce-Sc ribbons and at $x = 5$ in Al-Ni-Ce-Sc ribbons). The structure of such type showed the maximum hardening. A further increase of Sc content in Al-Ce-Sc ribbons led to vanishing the amorphous phase and to the formation of Al_3Sc and Al_4Ce intermetallics, the highest hardness was observed in the case when a structure of eutectic type was formed.

High-Temperature X-ray Investigation of $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ Powder with Quasicrystalline Component

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Structure and phase composition of Al-Cu-Fe powders atomized by high-pressure water are investigated. As-atomized powders had two phase components: a quasicrystalline phase of icosahedral symmetry (ψ) and lattice parameter $a_\psi = 0.63466(7)$ nm, and a bcc phase (β , $a_\beta = 0.29236(7)$ nm). The magnitude relation of phase amounts depended on powders particle size. X-ray *in situ* investigation (monochromatic $\text{CuK}\alpha$ radiation) in He environment of powders while heating revealed the occurrence in them of a complete phase transition $\beta \rightarrow \psi$ at temperature of 823-873 K after 1 h holding. It was accompanied by lowering the ψ -phase lattice period to the value $a_\psi = 0.63167(4)$ nm. The functional dependence of the ψ -phase lattice period in $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ powder in the temperature interval of 293-1123 K is established in the form:

$$a_\psi(T) = 0.62982 + 4.75933 \cdot 10^{-6}T + 5.40485 \cdot 10^{-9}T^2.$$

X-ray diffractometric analysis has shown the existence of the ψ -phase in the given powder sample to a temperature of 1143 K. Cooling the sample from 1173 K was accompanied by the appearance of ψ - and β -phases with lattice parameters different from ones in the starting powder. This difference is caused by a lower cooling rate in the X-ray chamber and a redistribution of chemical elements in the alloy.

Alloying Al-Cu-Fe powders by Sc and Cr led to changing the magnitude relation of ψ - and β -phases as well as of their lattice parameters in as-atomized condition and appearing new phase components at temperatures of 873-1073 K in process of powder heating.

Consolidation of Al-Cu-Fe powders with quasicrystalline component by using high quasihydrostatic pressures

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One of essential peculiarities of icosahedral quasicrystals is the absence of macroplasticity at low temperatures and pressures. It makes difficult the consolidation of quasicrystal powders that behave while pressing in many features like to powders of ceramic materials. Usually quasicrystalline powders are consolidated by the technique of HIP, but this process takes rather much time and requires rather complicated special equipment. In our former works it was shown that the consolidation of ceramic powders is significantly lightened by high quasihydrostatic pressure.

In this work there are presented the results of investigating the consolidation of quasicrystalline $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ powder with quasicrystalline component (ψ -phase) manufactured by melt atomization with high-pressure water. Changing the porosity of coldly compacted samples depending on the applied pressure ($0 < P < 5$ GPa) was studied. The increase of the pressure to 3.0–3.5 GPa is established to lead to a continuous consolidation of samples. In samples manufactured under pressures higher than 3.0 GPa a certain increase of the porosity was observed, and it was explained by the elastic aftereffect.

Using the obtained values of the porosity in the pressure region of 0.2–1 GPa and basing upon the phenomenological equation for a porous plastic billet, we have evaluated the average assessed value of the yield stress for the starting material as $\sigma_s \approx 0.6$ GPa. A porous body from the quasicrystalline powder is shown to behave under high quasihydrostatic pressures higher than 1 GPa as porous bodies from a plastic material.

Studying the influence of temperature (20–800 °C) on the consolidation of $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ powders under a pressure of 3 GPa with holding of 2 min has shown that the maximum relative density of the sample is achieved at a temperature of 700 °C. This temperature corresponds to the condition of Al-Cu-Fe ψ -phase stability and its ability to plastic deformation.

Thus, there are developed the conditions for consolidating quasicrystalline powders with using high pressures that is provided by preliminary cold pressing of a porous billet with subsequent hot pressing under high pressure. It is shown that the process of pressing powders under investigation with using high quasihydrostatic pressure can be described by the model of tough-plastic behavior.

Vickers hardness in samples consolidated at 700 °C is shown to lower with the growth of consolidating pressure in spite of increasing the sample density. It is a consequence of strain softening in the ψ -phase in process of pressing due to shear components of the pressing stress.

Structural Peculiarities of $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ Ingots with Quasicrystalline component

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For manufacturing ingots two techniques were used: the technique **1** of drawing the melt into a thin quartz tube; the technique **2** of melting in a copper water-cooled crystallizer with repeated remelting.

Structural state of ingots was characterized by the presence of the icosahedral quasicrystalline ψ -phase ($\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$), the β -phase with a cubic body-centered lattice ($\text{Al}_{55}\text{Cu}_{40}\text{Fe}_5$), and the λ -phase with a monoclinic lattice ($\text{Al}_{72}\text{Cu}_5\text{Fe}_{23}$). Particles of β - and λ -phases were embedded into the ψ -phase matrix.

The ingot of $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ alloy of 6 mm in diameter and about 80 mm in length manufactured by the technique **1** turned to be non-uniform in length. Thus, approximately in one third of the ingot from the beginning X-ray investigation revealed the existence of ψ -, β - and λ -phases, whereas in the remaining part of the ingot the amount of λ -phase was very insignificant. The ingot was annealed in vacuum at temperatures of 700 and 750 °C. A single-phase ψ -condition was obtained in the middle and end parts of ingot by annealing at 750 °C for 5 h. The prolongation of annealing the initial part of the ingot at 750 °C to 25 h did not led to obtaining the single-phase ψ -state. Structural state of ingots manufactured by drawing into a quartz tube of 13 mm in diameter was more uniform in length. The phase composition of this ingot was the same as of previous one, and the size of β and λ phase components was greater, evidently, due to lower crystallization rate. Annealing this ingot at 750 °C led to gradual lowering the intensity of X-ray peaks from β - and λ -phases, but prolongation the annealing time to 100 h did not convert it to the single-phase state.

The structural composition of $\text{Al}_{63}\text{Cu}_{25}\text{Fe}_{12}$ ingots produced by the technique **2** with various cooling rates was the same. Compared to ingots drawn into quartz tubes, particles of phases were more elongated. The size of phase components lowered with increasing the cooling rate. Annealing to the single-phase ψ -state at 750 °C was successful only for ingots manufactured with a cooling rate of 300 °C/s. It took 10 h. The maximum annealing time of all ingots was of 25 h, and in the rest of ingots it gave no single-phase state. It is interesting that the size of phase components in ingots manufactured by the techniques **1** и **2** that can be annealed to the single-phase ψ -state are approximately equal.

The batch of ingots produced by the technique **2** with a cooling rate of 300 °C/s was crushed into powder. The ratio of pear intensities of ψ -phase after crushing somewhat changed. These changes are explained by the elimination in powder of texture and inhomogeneities possible in the ingot. The amount of ψ -phase in this powder was of 55 wt. %. Along with elongated particles and particles with sharp edges the powder contains rather many particles of a polyhedral shape. Evidently, it is due to a high degree of symmetry in the icosahedral phase.